12.6 Analysis of Rawinsonde Spatial Separation for Space Launch Vehicle Applications at the Eastern Range

Ryan K. Decker
NASA/Marshall Space Flight Center, Huntsville, Alabama

1. INTRODUCTION

Space launch vehicles use day-of-launch steering commands based upon the upper-level (UL) atmospheric environments in order to alleviate wind induced structural loading and optimize ascent trajectory. Historically, UL wind measurements to support launch operations at the National Aeronautics and Space Administration's (NASA) Kennedy Space Center (KSC), co-located on the United States Air Force's Eastern Range (ER) at the Cape Canaveral Air Force Station use high-resolution (HR) rawinsondes. One inherent limitation with rawinsondes is the approximately one-hour sampling time necessary to measure tropospheric winds. Additionally, rawinsonde drift during ascent due to the ambient wind environment can result in the balloon being hundreds of kilometers down range, which results in questioning whether the measured winds represent the wind environment the vehicle will experience during ascent. This paper will describe the use of balloon profile databases to statistically assess the drift distance away from the ER launch complexes during HR rawinsonde ascent as a function of season. Will also discuss an alternative method to measure UL wind environments in closer proximity to the vehicle trajectory when launching from the ER.

2. DATA SOURCES

The use of HR (30.4m/100-ft interval) rawinsonde systems have historically been the primary source of tropospheric wind measurements at the ER. The HR rawinsonde systems used at the ER consist of a specially designed balloon, known as a Jimsphere, which has conical roughness elements to reduce balloon oscillation and a vent to maintain constant volume during ascent (Figure 1). Due to the vent valve maintaining a constant volume during ascent, the balloons typically reach a buoyancy equilibrium state at approximately 16.1-17.7 km (53-58 kft). Over the past 50 years, the ER has used two types of HR rawinsonde systems to measure tropospheric winds. One system uses ground based radar to track a Jimsphere balloon (Wilfong et al., 1997). The next generation system, known as the Automated Meteorological Profiling System (AMPS) High Resolution Flight Element (HRFE), has incorporated the use of Global Positioning System (GPS) technology into the instrumentation package which is tethered to a clear Jimsphere (Divers et al. 2000). The GPS capability allows for multiple HRFE (up to 6) releases while reducing the need for ground based radar tracking system necessary for tracking Jimsphere ascent.

Corresponding author address: Ryan K. Decker, NASA/MSFC, Mail Code EV44, Huntsville, AL 35812; email: ryan.k.decker@nasa.gov

Figure 1. The AMPS HRFE with a clear Jimsphere.

The HR tropospheric wind measurements are necessary to determine the structural loads placed on the space launch vehicle from atmospheric winds during ascent (Karlgaard et al., 2013). The use of HR wind profiles supports various activities throughout the lifecycle of a launch vehicle program. In the vehicle design phase, databases of individual wind profiles are used in monte carlo trajectory simulations to assess vehicle performance and structural robustness over a wide range of wind environments (Hanson and Hall, 2008). Databases of time correlated wind profiles can also be constructed to assess temporal variability in developing "knockdowns" used to protect the vehicle from wind change between the time of measurement and flight (Smith and Austin, 1983). For day-of-launch operations, HR tropospheric wind measurements are used in

trajectory design to optimize vehicle performance and for structural load assessments (Decker and Leach, 2004).

The NASA/Marshall Space Flight Center's Natural Environments Branch (NEB) maintains an archive of tropospheric wind profiles from all meteorological observations at the ER including atmospheric profiles from both HR wind measurement systems. Wind profiles from the NEB Jimsphere system archive have a period of record (POR) from 1989-2015 consisting of 1696 profiles and AMPS HRFE from 2002-2015 with 840 profiles for a total of 2536 profile. Each wind profile reports wind speed, wind direction and balloon rise rate at 30.4 m (100-ft) intervals from the surface to termination altitude. The tropospheric wind profiles in the NEB archive have varying altitude coverage due to the operational usage. Often during launch operations balloons are tracked for limited altitudes, experience loss of GPS signal or the balloon fails resulting in an inconsistent vertical coverage. For this analysis any wind profile that didn't reach a minimum of 15.2 km (50 kft) was omitted which occurred in 407 of the 2536 profiles.

3. ANALYSIS

The UL wind environment over the Florida peninsula has a distinctive seasonal variation. The winter season is associated with stronger wind aloft as the UL jet core tends to migrate southward over the southeastern US. Whereas in the summer season, high pressure ridges set-up over the western Atlantic, forcing the UL jet core north, with light winds aloft. For these reasons, when analyzing UL wind statistics for the ER the data are broken down into three seasonal groups; winter, summer and transition. The winter season consists of the months December, January, February and March. The summer season are the months of June, July, August and September with the remaining months, October, November, April, May, defining the transition season. The number of profiles for each season in the NEB database ranged from 604 profiles in the summer to 792 profiles during the transition months. The winter season had 733 profiles. To determine the downrange distance during balloon ascent either the direct GPS position information is necessary (HRFE only) or through derivation of the approximate position by calculating the change of position throughout ascent from use of the wind speed and direction plus the ascent rise rate. The later method of deriving the downrange distances was used in this study. In order to calculate the balloon position, the first step was to convert all reported wind speed and direction into the u and v wind components to determine the change in the meridional (North/South) and zonal (East/West) displacement. Next the wind components and rise rate were layer averaged. At each consecutive altitude interval, usually 30.4 m (100 ft), the average wind was multiplied by the height and divided by average rise rate as shown in equations 1 and 2.

$$dx_i = \frac{\bar{u} * z_i}{\overline{rr}} \quad (1)$$

$$dy_i = \frac{\bar{v} * z_i}{\overline{rr}} \quad (2)$$

After each displacement was calculated, the result was added to the sum of all level displacements up to that altitude in order to get the total zonal and meridional displacement starting from the surface.

$$x_i = x_{i-1} + dx_i \quad (3)$$

$$y_i = y_{i-1} + dy_i \quad (4)$$

Finally, the distance away from the balloon release facility at each altitude level was calculated by taking the root sum squared of the sum of the meridional and zonal distances.

$$dist_i = \sqrt{(x_i)^2 + (y_i)^2} \quad (5)$$

where *dist* is the downrange distance from the balloon release facility as a function of altitude. Results from the spatial separation analyses will be presented as a function of the three seasons. Figure 2 is an illustration of the spatial separation as a function of season. Depicted in Fig. 2 are the 50 percentile downrange distance of HR rawinsondes for the three seasons plus the database maximum downrange distance.

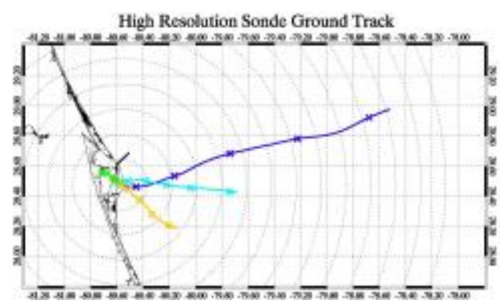

Figure 2. Selected profiles representing the 50th percentile downrange distance of HR rawinsondes for winter (cyan), summer (green), and transition (gold) along with the database max (blue). Solid black line is the STS-117 trajectory to 23 km (~90 kft). The "x" in the profiles represents 3.1 km (10 kft) intervals.

With the downrange distances calculated for all the profiles, the data were sorted through several statistical methods to quantify extent of spatial separation. Figure 3 depicts the empirical

cumulative probability distribution of all the profiles that reached a minimum of 15.2 km (50 kft) broken down into seasons and annually. Typically, the high resolution balloons reach 17 km (55 kft) before they begin to float. Results are consistent with the climatological UL wind environment; stronger winds in the winter result in further downrange drift while lighter winds in the summer result in less downrange drift. Annually, the 50^{th} percentile downrange distance is approximately 50 km (31 miles) downrange but for the winter season the 50^{th} percentile is 83 km (52 miles). A disparity is also apparent between the winter and summer season for all probability levels above the 50^{th} percentile level with the maximum winter distance exceeding 200 km (124 miles) whereas in the summer the maximum was 92 km (57 miles). The extreme probability levels, > $99^{\%}$, are close because the beginning and end months in transition season are close to the winter season.

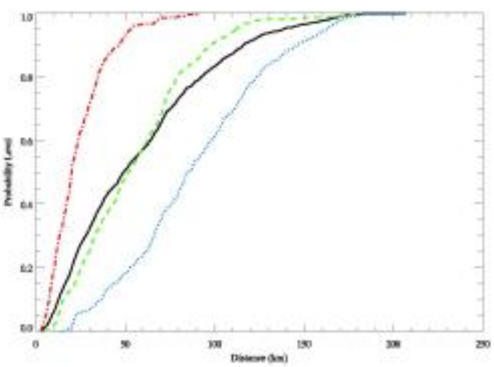

Figure 3. Empirical cumulative probability distributions of maximum downrange distance reached of HR rawinsondes released from the ER for winter (blue), transition (green), summer (red) and annual (black).

Figures 4-8 are also empirical cumulative probability distributions for downrange distances but are shown at 3.0 km (10 kft) levels starting at 3 km (~10 kft) up to 15 km (~50 kft). The distributions have similar trends at each altitude level where the summer month distances are short and balloons remain close to the ER and longer downrange distances in the winter.

The long downrange distances the balloons travel during day-of-launch operations are usually associated with strong UL wind environment. During dynamic conditions the measurements from the balloons could differ from those directly above the ER as measured by a vertically pointing Doppler Radar Wind Profiler (DRWP) operated by NASA KSC. When differences are observed, the validity of the balloon measurements that are used in the

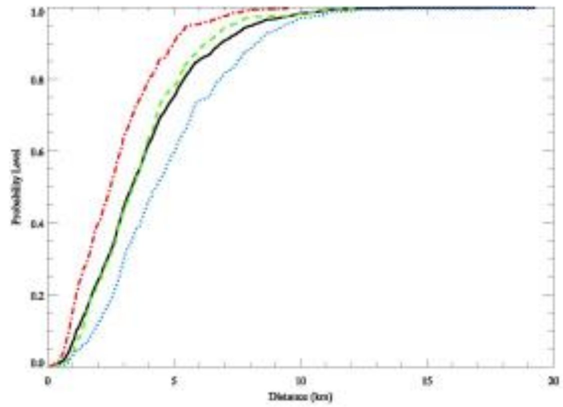

Figure 4. Empirical cumulative probability distributions of maximum downrange distance reached at 3.0 km (~ 10kft) altitude of HR rawinsondes released from the ER for winter (blue), transition (green), summer (red) and annual (black).

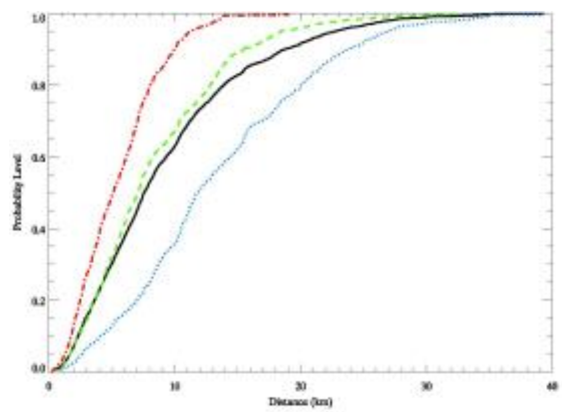

Figure 5. Empirical cumulative probability distributions of maximum downrange distance reached at 6.1 km (~20 kft) altitude of HR rawinsondes released from the ER for winter (blue), transition (green), summer (red) and annual (black).

trajectory design are questioned and if those differences observed will affect the safety of the vehicle. Recently, NASA KSC has replaced the old 50-MHz DRWP with a new Tropospheric DRWP system which includes new hardware and software (Wilfong et. al, 2014). At the same time, NASA began development of the Space Launch System (SLS) vehicle as the replacement to the Space Shuttle. The SLS program is utilizing databases of wind profiles from the DRWP for use in SLS trajectory design and certification. The DOL SLS trajectory simulations require wind and thermodynamic data from the surface to 183 km (600 kft). These data will consist of a combination of DOL measurements, up to 30 km (100 kft), and monthly mean climatology data from 30 to 183 km (100 to 600 kft).

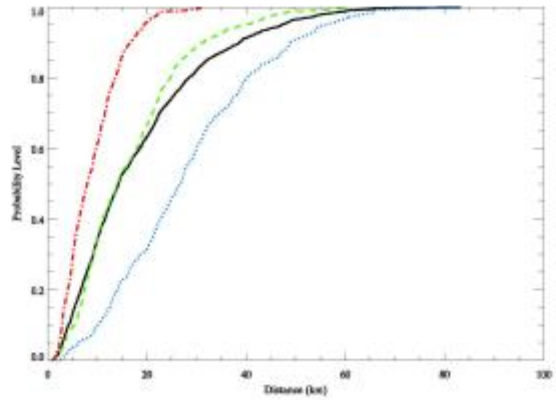

Figure 6. Empirical cumulative probability distributions of maximum downrange distance reached at 9.2 km (~ 30 kft) altitude of HR rawinsondes released from the ER for winter (blue), transition (green), summer (red) and annual (black).

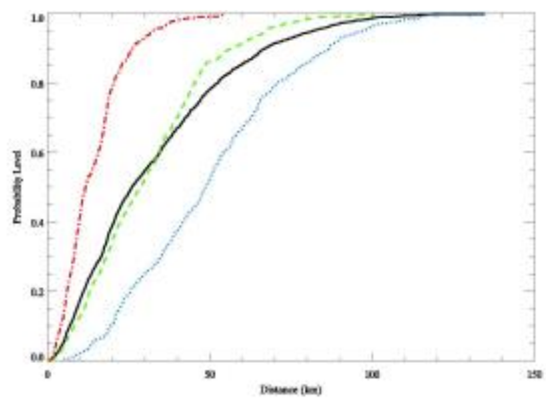

Figure 7. Empirical cumulative probability distributions of maximum downrange distance reached at 12.2 km (~ 40 kft) altitude of HR rawinsondes released from the ER for winter (blue), transition (green), summer (red) and annual (black).

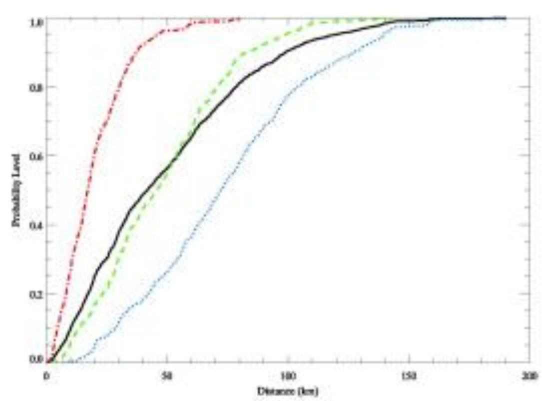

Figure 8. Empirical cumulative probability distributions of maximum downrange distance reached at 15.2 km (~50 kft) altitude of HR rawinsondes released from the ER for winter (blue), transition (green), summer (red) and annual (black).

4. PROFILE ENVISION AND SPLICING TOOL (PRESTO)

The NEB has developed the Profile Envision and Splicing Tool (PRESTO), a software which can ingest multiple data sources, including the DRWP, to generate a vertically complete wind and thermodynamic profile in effort to generate the most spatially consistent representation of the UL atmospheric environment the vehicle may experience during ascent. The software incorporates algorithms which splices data together and preserves spectral content down to the wavelength resolvable by the coarsest measurement system (Decker et. al., 2015). Selection and visualization of all available profiles is handled through a graphical user interface (GUI). There are two GUI that PRESTO invokes. The first GUI is for the operator to set the range of dates for the software to search for available profiles (Figure 9). The second GUI provides the user with a listing of all available profiles over a selected timeframe and allows them to select which profiles to splice together and specify the wavelength to filter the data. After the software performs the splicing and filtering, the data from input profiles and resultant output are displayed to visualize how the generated profile compares to the input sources. Figure 10 shows the GUI along with the output from the splicing and filtering algorithms overlaid with the input sources. If the mathematically generated profile is deemed acceptable it is written to an output file and provided for use in vehicle trajectory simulations.

Figure 9. PRESTO data input GUI where the user selects the desired date range and directories to search for atmospheric profiles.

5. SUMMARY

Databases of HR rawinsondes were used to statistically assess the spatial separation during ascent from the ER launch complexes as a function of season and annually. Results are consistent with the climatological UL wind environment over central

Florida; stronger winds in the winter result in further downrange drift while lighter winds in the summer result in less downrange drift. In support of launch vehicle operations, the long distances balloons drift downrange from the ER bring into question whether the measured winds represent the wind environment the vehicle will experience during ascent. The PRESTO software program developed by the MSFC NEB provides a method to ingest multiple data sources, including the KSC DRWP, to generate a vertically complete wind and thermodynamic profile that provides the most spatially consistent representation of the UL atmospheric environment for use in launch vehicle trajectory assessments. This capability is planned for use by NASA SLS for the vehicle's first flight scheduled for Fall 2018.

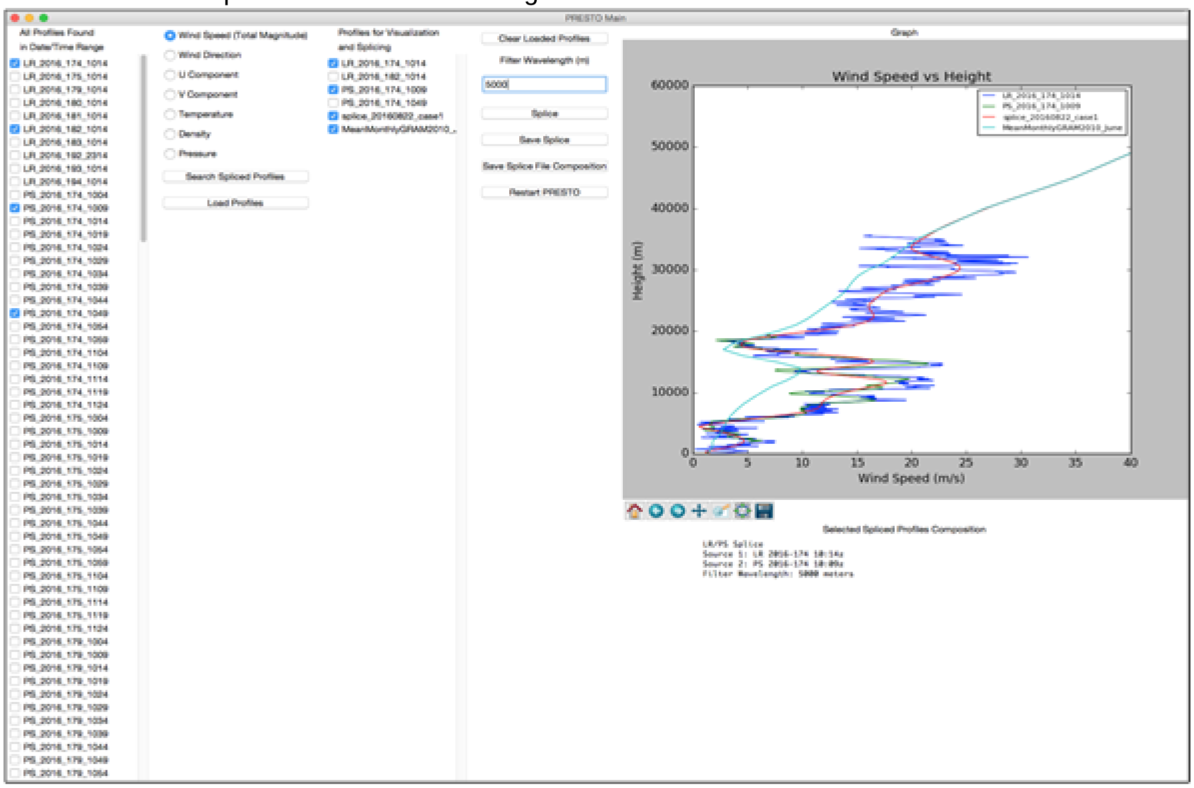

Figure 10. The main PRESTO GUI where the user can select profiles to load, which profiles to splice together, set the filtering wavelength, the variables to visualize, the display of the input and output profiles and save the spliced profile to a local directory.

6. REFERENCES

Decker, Ryan K., R. E. Barbre Jr., R. Leach, J. R. Walker, and J. Brenton, 2015: Assimilation of wind profiles from multiple Doppler Radar Wind Profilers for space launch vehicle applications. 19th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), 4-8 January 2015, Phoenix, AZ, Amer. Meteor Soc, Boston MA.

Decker, Ryan K., and Richard Leach. "Tropospheric Wind Monitoring During Day-of-Launch Operations for National Aeronautics and Space Administration's Space Shuttle Program." 11th AMS Conference on Aviation, Range and Aerospace Meteorology, 4-8 Oct. 2004, Hyannis, MA, Amer. Meteor Soc, Boston MA.

Divers, R.P., A.Z. Chandler, P. Viens, K. Bzdusek, G. Herman, R. Hoover, and T. Mitchell, 2000: Automated meteorological profiling system (AMPS) description. 9th Conf on Av. and Range Meteor. Orlando, FL, Amer. Meteor Soc, Boston MA.

Hanson, John M., and Charlie E. Hall. "Learning about Ares I from Monte Carlo simulation." *AIAA Guidance, Navigation and Control Conference and Exhibit*. 2008.

Karlgaard Christopher D., Roger E. Beck, Stephen D. Derry, Jay M. Brandon, Brett R. Starr, Paul V. Tartabini, and Aaron D. Olds. "Ares I-X Trajectory Reconstruction: Methodology and Results", Journal of Spacecraft and Rockets, Vol. 50, No. 3 (2013), pp. 641-661.

Smith, Orvel E, and L. D. Austin. "Space shuttle response to ascent wind profiles." *Journal of Guidance, Control, and Dynamics* 6.5 (1983): 355-360.

Wilfong, Tim, S.A. McLaughlin and E. Lau. "Kennedy Space Center 50-MHz Launch Support Radar Wind Profiler." 17th Symposium on Meteorological Observations and Instrumentation, 8-13 June 2014, Westminster, CO, Amer. Meteor Soc, Boston MA.

Wilfong, T. L., S. A. Smith, and C. L. Crosiar, 1997: Characteristics of High-Resolution Wind Profiles Derived from Radar-Tracked Jimspheres and the Rose Processing Program. J. Atmos. Oceanic Technol., 14, 318-325.